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K.D. Lawson[1*], M. Groth[2], P. Belo[1], S. Brezinsek[3], G. Corrigan[1], A. Czarnecka[4], E. Delabie[5], P. Drewelow[6], D. Harting[3], I. KsiąŜek[7], C.F. Maggi[8], C. Marchetto[9], A.G. Meigs[1], S. Menmuir[10], M.F. Stamp[1], S. Wiesen[3] and JET-EFDA Contributors[*]

[1]CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK
[2]Aalto University, Association EURATOM-Tekes, Espoo, Finland
[3]Forschungszentrum Jülich, IEK-4 Plasmaphysik, Jülich, Germany
[4]Institute of Plasma Physics and Laser Microfusion, Association EURATOM-IPPLM Warsaw, Poland
[5]FOM Institute DIFFER, Nieuwegein, The Netherlands
[6]MPI für Plasmaphysik, EURATOM Association, Greifswald, Germany
[7]Institute of Physics, Opole University, ul.Oleska 48, 45-052 Opole, Poland
[8]MPI für Plasmaphysik, EURATOM Association, D-85748, Garching, Germany
[9]Istituto di Fisica del Plasma, CNR, Milano, Italy
[10]Euratom/VR Association, KTH Royal Institute of Technology, SE-100 44, Stockholm, Sweden

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Improved EDGE2D-EIRENE simulations of JET ITER-like wall L-mode discharges utilising poloidal VUV/visible spectral emission profiles

K D Lawson[a*], M Groth[b], P Belo[a], S Brezinsek[c], G Corrigan[a], A Czarnecka[d], E Delabie[e], P Drewelow[f], D Harting[c], I Książek[g], C F Maggi[h], C Marchetto[i], A G Meigs[a], S Menmuir[j], M F Stamp[a], S Wiesen[c] & JET-EFDA Contributors[1]

JET-EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK

[a]CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK

[b]Aalto University, Association EURATOM-Tekes, Espoo, Finland

[c]Forschungszentrum Jülich, IEK-4 Plasmaphysik, Jülich, Germany

[d]Institute of Plasma Physics and Laser Microfusion, Association EURATOM-IPPLM Warsaw, Poland

[e]FOM Institute DIFFER, Nieuwegein, The Netherlands

[f]MPI für Plasmaphysik, EURATOM Association, Greifswald, Germany

[g]Institute of Physics, Opole University, ul.Oleska 48, 45-052 Opole, Poland

[h]MPI für Plasmaphysik, EURATOM Association, D-85748, Garching, Germany

[i]Istituto di Fisica del Plasma, CNR, Milano, Italy

[j]Euratom/VR Association, KTH Royal Institute of Technology, SE-100 44, Stockholm, Sweden

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**Corresponding author address:* K1-1-40, Culham Science Centre, Abingdon, OX14 3DB, UK

**Corresponding author E-mail:* Kerry.Lawson@ccfe.ac.uk

Presenting author: Kerry Lawson

Presenting author E-mail: Kerry.Lawson@ccfe.ac.uk

[1] See the Appendix of F. Romanelli et al., Proc. of the 24th IAEA Fusion Energy Conference 2012, San Diego, USA

Abstract

A discrepancy in the divertor radiated powers between EDGE2D-EIRENE simulations, both with and without drifts, and JET-ILW experiments employing a set of NBI-heated L-mode discharges with step-wise density variation is investigated. Results from a VUV/visible poloidally scanning spectrometer are used together with bolometric measurements to determine the radiated power and its composition. The analysis shows the importance of D line radiation in contributing to the divertor radiated power, while contributions from D radiative recombination are smaller than expected.

Simulations with W divertor plates underestimate the Be content in the divertor, since no allowance is made for Be previously deposited on the plates being re-eroded. An improved version of EDGE2D-EIRENE is used to test the importance of the deposited layer in which the sputtering yield from supposed pure Be divertor plates is reduced to match the spectroscopic signals, while keeping the sputtering yield for the Be main chamber walls unchanged.

1. Introduction

An understanding of the behaviour of the plasma edge and divertor physics is essential for the design of next-step machines such as ITER, for which JET with its ITER-Like Wall (ILW) of Be in the main chamber and W in the divertor is ideally suited. Both fuel and edge impurities affect the power balance, thus determining the power reaching the divertor-target plates, which is limited by the mechanical and thermal properties of the plates. A recent comparison [1] of L-mode discharges during the present JET-ILW campaign and previous JET-C campaigns, in which the plasma-facing surfaces were C based materials (Carbon-Fibre Composite), has consistently shown a shortfall in the radiated power in the Scrape-Off Layer (SOL) and divertor calculated from EDGE2D-EIRENE simulations [2] below that measured by bolometry. In order to understand this discrepancy, the contributions to the divertor radiated power (P_{rad}) as predicted by the simulations have been quantified and the results compared with measurements from bolometry and an upgraded poloidally scanning VUV/visible spectrometer.

2. The poloidally scanning VUV / visible spectrometer

The spectrometer [3] has two systems, one with a vertical view of the divertor, the other looking from a horizontal port towards the top of the inner wall. Each system includes a VUV spectrometer, which measures 2 spectral lines within the wavelength range ~200 to 1500 Å and a visible telescope that observes D_{α}, D_{β} and two lines each of Be, C and W using PMT/filter combinations, together with a Czerny-Turner spectrometer. The poloidal scan of ~125 ms (vertical) and ~105 ms (horizontal) is achieved by compact oscillating mirrors outside the torus vacuum. Results from the divertor view are presented here. Modifications have been made to enable the VUV D Ly_{α} emission of the Lyman spectroscopic series to be measured in the future. Until now, its high intensity has caused charge depletion saturation, preventing its reliable measurement.

3. Deuterium simulations

The simulations of the JET-ILW, L-mode, NBI-heated discharges of Groth *et al.* [1] have been used to determine P_{rad} contributions (table 1). They apply to a density scan series of 2.5MA / 2.5T discharges (81472-81492) heated with 1.1, 1.2 or 1.6MW of NBI. The simulations are listed under discharge 81472 and have D fuel with Be and W impurities. They have been carried out for a range of outer midplane separatrix densities, $n_{e,sep}$, (7×10^{18} m^{-3} up to the maximum at which the simulations converge of 2-2.2×10^{19} m^{-3}). A range of powers transported across the separatrix into the SOL was considered, although results are only presented for the extreme cases of 2.2 and 2.8 MW. The version of the EDGE2D-EIRENE code adapted to include D_2 and D_2^+ molecules was used [4], together with a new version that includes drifts. This latter is run without impurities and results will be presented only for 2.2 MW power to the SOL, little difference being found when this parameter was varied in the no drift cases. To allow comparisons with the bolometric and spectrometer measurements, the contributions are integrated along the diagnostic lines-of-sight. It was necessary to subtract a contribution of 1.3×10^4 W/m^2 from the bolometric signals to account for core radiation, although the D emission predominately comes from the divertor region.

4. Contributions to the divertor radiated power (P_{rad})

The simulations show the importance of D to P_{rad}, the impurities each accounting for no more than a few per cent [5]. These pulses therefore provide a stringent test of the simulations for the D fuel. P_{rad} for the Be impurity is obtained from the simulations described in section 6.

Among the D contributions, the largest component is due to D (Lyman) line radiation, in particular from the Ly_α line. P_{rad} due to free electron recombination, which for D is radiative recombination, can also be significant. However, at most $n_{e,sep}$, these simulations would suggest a very small contribution of free electron recombination to P_{rad}. An estimate of the VUV electronic line radiation from D molecules (D_2 and D_2^+), which because of its wavelength is expected to be a significant component of the total molecular radiation, is obtained by assuming the same electron collisional excitation and radiative decay rates as for D atoms.

5. Comparisons with measured profiles

To gain understanding of the radiated power discrepancy, comparisons are made between measured and simulated bolometric and spectroscopic profiles. In all cases the profiles are plotted against major radius, R, measured at a height of z = -1.6 m. At most T_e, the D line power can be calculated from 1.03 * (Ly_α + Ly_β line intensities), the 3% accounting for all other D lines. The line power calculated from Ly_β / D_α relies on the simulated Ly_α / Ly_β ratio (figure 1). In figures 2 to 4 measured P_{rad} profiles from bolometry (figures a) and the D line power profile calculated from spectroscopy (figures b), are compared with the corresponding simulations for three $n_{e,sep}$. Four measured profiles are illustrated at each density. The parameter used to match the measurements to the simulations, $n_{e,sep}$, is a control parameter in the simulations, but is extremely difficult to determine reliably for high $n_{e,sep}$ discharges with their steep edge gradients. Since there is an approximately linear relationship between $n_{e,sep}$ and an edge line-averaged interferometric measurement of n_e [6], the simulations are matched to particular discharges at low values of $n_{e,sep}$ and the more reliably determined line-averaged measurement of n_e used to relate the simulations to the higher density discharges.

At low $n_{e,sep}$ (figure 2), the simulation of the inner divertor plasma underestimates the bolometric signal, the simulation having a narrower strike-point feature close to the vertical-target plate (R=2.4 m). It can be seen that forward drifts, which have the greatest effect at low $n_{e,sep}$, increase the power radiated by this feature, but its position and width are unaltered. The D line power emits away from the target and, although consistent with the bolometric profile at these radii, does not explain the intense, broad bolometric feature. There is no evidence that radiation from molecules is playing a significant role. Most evident in the outer divertor they tend to increase the measured - simulated discrepancy in this region. The simulation calculates low levels of D radiative recombination (a few per cent) at these $n_{e,sep}$, this channel only becoming significant at a T_e ~1eV. Nevertheless, this is the only mechanism that can give rise to the significant radiation seen by the bolometers and would suggest that the electron temperatures in the simulation (typically 4-60eV, depending on $n_{e,sep}$) are too high.

With increasing $n_{e,sep}$ the simulated inner strike-point peak remains narrow and close to the target (figures 3-4). The calculated D line power in the inner divertor becomes significantly higher than would be expected from bolometry. This is most easily explained by the calculation of the Ly_α intensity being too high. Figure 1 shows that, above $n_{e,sep}$ of 1.6×10^{19} m^{-3}, as $n_{e,sep}$ increases and the overall temperature decreases, the Ly_{α} / Ly_{β} ratio has a clear downward trend, which would give the required lower Ly_{α} intensity. Again, this implies that the simulation temperatures are too high, particularly in the inner divertor. Measurement of the Ly_{α} line intensity as well as of high n lines would provide confirmation.

6. Comparisons with measured Be emission profiles

EDGE2D-EIRENE simulations with a W divertor underestimate the Be emission from the divertor, since no allowance is made for the previous deposition of Be onto the divertor plates during plasma operations [7] and its subsequent release during a pulse. This process adds to the Be ion density in the divertor region, beyond that transported from the torus walls. In the absence of a sputtering model describing Be deposited on W surfaces, this was simulated by supposing pure Be divertor plates (i.e. all plasma facing surfaces being Be), but with a reduced sputtering yield. In some initial simulations the reduction in the Be sputtering yield was applied to all Be surfaces, including the Be walls. An improved version of EDGE2D-EIRENE allows separate control of the sputtering yield on the divertor plates, the divertor private region and the vessel walls. Figure 5 shows that the yield in the divertor region must be reduced by ~×10-20 to match the measured 527nm, Be II inner strike-point feature. The high simulated Be intensities found above the outer divertor throat and the low intensities at the corresponding position on the inboard side are expected to be brought closer to observations by the inclusion of drifts. Drifts would also be expected to increase the magnitude of the inner strike-point feature. Consequently, a reduction in the sputtering yield in the divertor region of ~×20 is expected to give the best agreement with the experimental measurements. This value is consistent with the influx to the target plates as predicted by ERO [8] and WallDyn [9] modelling.

7. Conclusions

Comparisons between EDGE2D-EIRENE simulations and measurements of P_{rad} in a density scan series of L-mode, NBI-heated discharges emphasize the importance of D and suggest that the simulation temperatures are too high, with the consequent underestimation of D radiative recombination. The inclusion of forward drifts in the simulations reduces the discrepancies, but insufficiently to account for the differences. D_2 and D_2^+ molecules do not appear to play a major role in the power balance of the divertor emission, although their importance will increase with decreasing temperature.

To account for the observed Be emission profiles across the divertor, it is necessary to take account of Be deposited on the W divertor plates during plasma operations, being subsequently re-eroded during a pulse. An improved version of the EDGE2D-EIRENE code enables the independent reduction of the Be sputtering yield in the divertor without the vessel walls being affected. Reducing the divertor sputtering yield by ~×20 from that which would apply to pure Be divertor plates is in reasonable agreement with the Be spectroscopic measurements at low densities demonstrating that this is a non-negligible effect. It is consistent with ERO and WallDyn modelling of Be.

Acknowledgements

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Table 1. Contributions to the divertor radiated power.

Contributions from D+Be+W simulations	
Line radiation from D.	Ly_α ~85-90%, Ly_β ~10% and other lines ~3%.
D line radiation due to recombination directly populating excited D atomic levels.	$<10^{-5}$ of D line radiation.
Line radiation from D_2 molecules.	~10% of D line radiation.
Line radiation from D_2^+ molecules.	~3% of D line radiation.
D charge exchange recombination	Negligible
Radiative recombination to D followed by cascading + Bremsstrahlung.	$<10^{-2}$ at low $n_{e,sep}$, rising to ~30% at high $n_{e,sep}$.
Contributions from D+Be simulations (section 6)	
Be impurity radiation.	Variable - few % in cases considered.
Estimated contributions	
C and O impurity radiation.	Variable - similar to Be.
High Z impurity (Ni, Cu and W) line radiation.	Generally smaller than low Z elements at the low T_e of the divertor.

Figure Captions

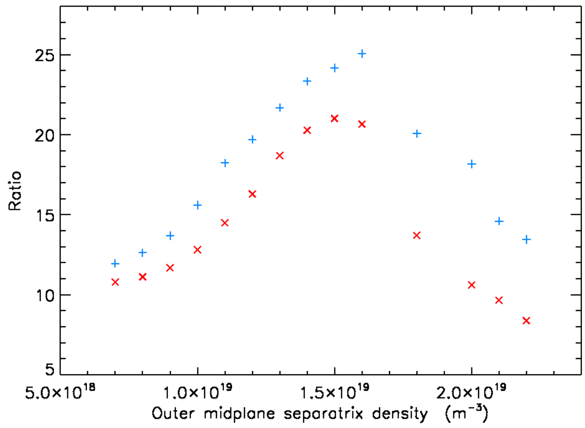
Figure 1. Ratio of simulated Ly_α to Ly_β emission integrated along the spectrometer line-of-sight with the profile averaged over the inner divertor (R=2.31-2.53m, +) and outer divertor (R=2.53-2.94m ×). Power to SOL in the simulations is 2.2 MW.

Figure 2. Comparison of a) bolometric radiated powers, b) calculated D line powers for pulse 81472 at 10 s, $n_{e,sep}=8.3\times10^{18}$ m^{-3}. Measured data (4 curves) without symbols (bolometric powers 1.3×10^4 W/m^2 core emission subtracted). Simulated data + no drifts, Δ with drifts 2.2 MW power to SOL, × no drifts 2.8 MW power to SOL. Simulated D line powers —— total, ---- without D molecular component.

Figure 3. Comparison of a) bolometric radiated powers, b) calculated D line powers for pulse 81480 at 17 s, $n_{e,sep}=1.4\times10^{19}$ m^{-3}. Measured data (4 curves) without symbols (bolometric powers 1.3×10^4 W/m^2 core emission subtracted). Simulated data + no drifts, Δ with drifts 2.2 MW power to SOL, × no drifts 2.8 MW power to SOL. Simulated D line powers —— total, ---- without D molecular component.

Figure 4. Comparison of a) bolometric radiated powers, b) calculated D line powers for pulse 81472 at 13 s, $n_{e,sep}=1.5\times10^{19}$ m^{-3}. Measured data (4 curves) without symbols (bolometric powers 1.3×10^4 W/m^2 core emission subtracted). Simulated data + no drifts 2.2 MW power to SOL, × no drifts 2.8 MW power to SOL. Simulated D line powers —— total, ········ without D radiative recombination and ---- also without D molecular component.

Figure 5. Simulated 527nm, Be II line intensity profiles (—— ×0.1 reduction, ---- ×0.05 reduction in divertor sputtering yield), 2.2 MW power to SOL, $n_{e,sep}=8.0\times10^{18}$ m^{-3}. Other (3) lines are observed emission profiles for pulse 81472 ~10 s.



Ratio
25
20
15
10
5
5.0×10^18
1.0×10^19
1.5×10^19
2.0×10^19
Outer midplane separatrix density (m^-3)

Figure 1.

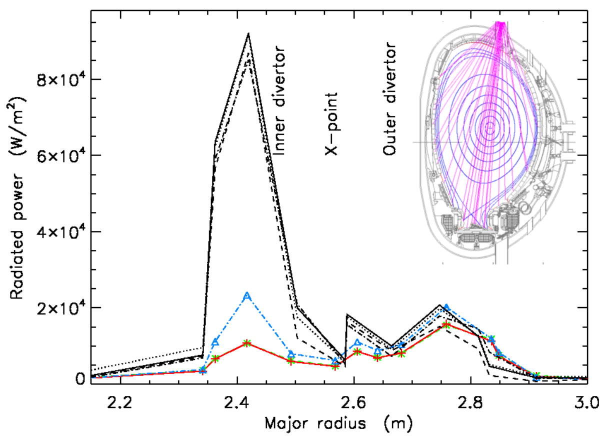


Figure 2a.

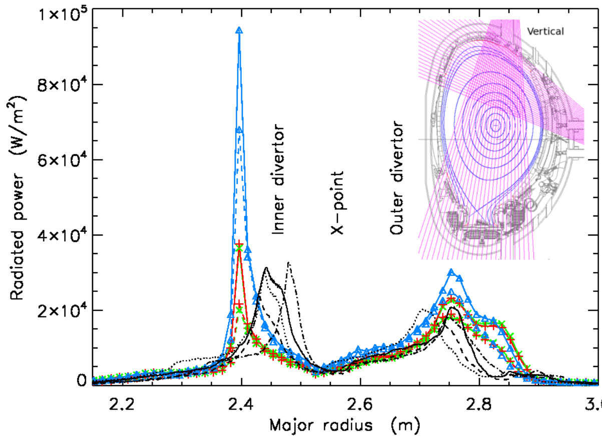


Figure 2b.

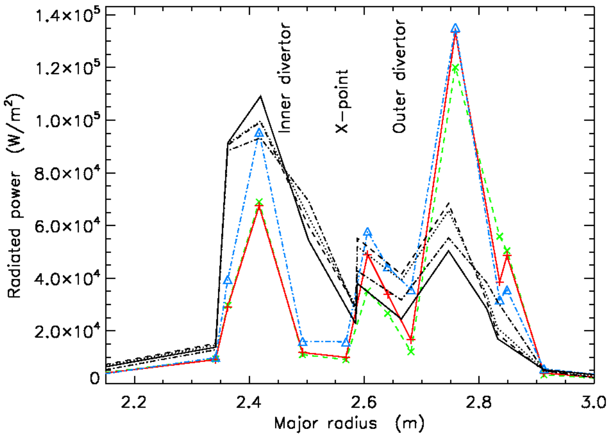


Figure 3a.

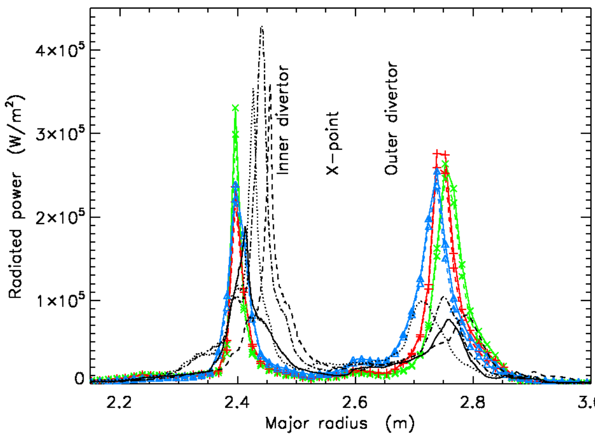


Figure 3b.

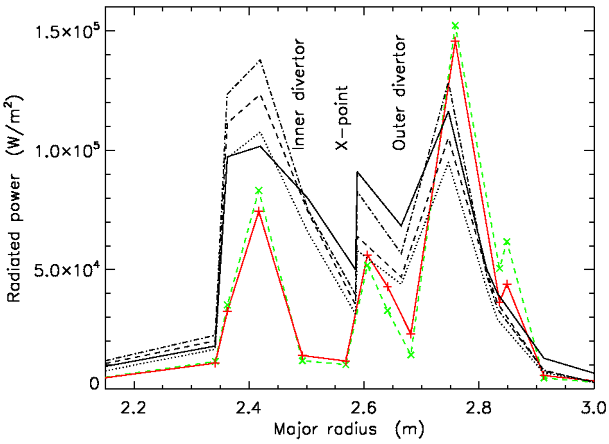


Figure 4a.

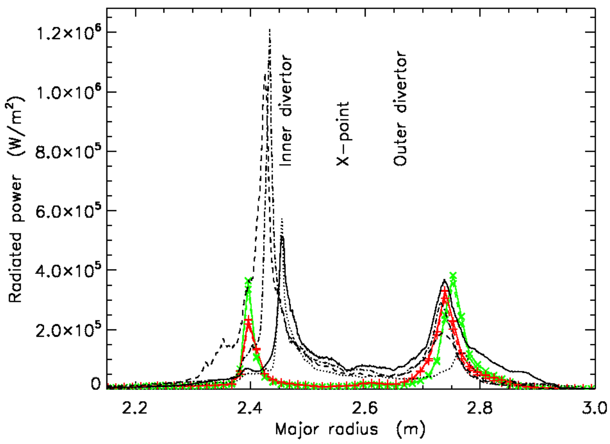
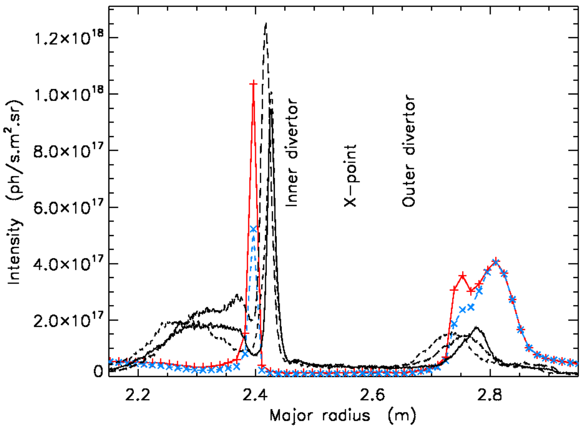


Figure 4b.



1.2×10^18
1.0×10^18
8.0×10^17
6.0×10^17
4.0×10^17
2.0×10^17
0
Intensity (ph/s.m^2.sr)
2.2
2.4
2.6
2.8
Major radius (m)
Inner divertor
X−point
Outer divertor

Figure 5.